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To what extent can solar control be effective in enhancing indoor comfort in a fully glazed office building?

H Farouk¹ and H Elsharkawy¹

¹ Department of Architecture and Visual Arts, School of Architecture, Computing and Engineering, University of East London, UK, E162RD

Abstract. It is acknowledged that people spend almost 90 percent of their time in indoor spaces. Therefore, achieving a comfortable indoor environment that encourages productivity is crucial, particularly in office buildings. This paper investigates the design and performance of a modern office building in London characterized by fully glazed facades of open plan office spaces with no natural ventilation. The purpose of the research is to investigate the correlations between the control of direct solar radiation access and the effect on occupants' thermal comfort in the summer followed by assessing the potential effect of the application of passive solar shading on thermal comfort levels in the office spaces. The research methodology involves a survey questionnaire undertaken with employees of the office building, followed by dynamic thermal modelling of the building using Integrated Environmental Solutions (IES) software. The questionnaire has been designed to understand occupants' experiences within their office spaces and their strategies to improve the indoor environment. Furthermore, IES modelling and simulation provide in depth understanding of the building thermal performance and investigating the solar shading strategies. Overall, 66 questionnaire forms were completed where preliminary results demonstrated that most employees relied heavily on secondary cooling and heating systems to adjust the indoor air temperature for more satisfactory thermal comfort levels in their office spaces. The building modelling and simulation is used to quantify the direct solar radiation accessing the office space, the risks of overheating and the potential impact of solar control on occupants' indoor comfort. The findings from this study demonstrate the potentially high hours of discomfort in the summer within the office spaces mainly due to the lack of control of direct solar access through the extensive area of glazed facades. In order to maintain the thermal environment within the comfort level threshold in the warmer seasons a solar shading strategy should be considered.

1. Introduction and research context

The UK has been facing significant issues with workers' productivity which directly affect the country's economic growth. The Office for National Statistics (1) has found that the UK worker is 36% less productive than a German worker on a GDP per hour worked. Gupta et al. (2018) indicated that some human factors that influence productivity include stress, workplace politics, management effectiveness, health and comfort. Research into aspects that influence occupants' productivity in office spaces has been the focus of much of the recent decades' investigations; internal environmental quality (IEQ) being one of them. In fact, in a review of the relevant literature study, researchers identified eight IEQ factors that bear direct impact on occupants' productivity; office layout, thermal comfort, indoor air quality, noise and acoustics, lighting, location and feel, location and amenities, biophilia and views (2). However, the study found that the most significant factors are: thermal comfort, indoor air quality, office layout and noise and acoustics. Concerning thermal comfort; there are two main aspects that help determine it: physical thermal conditions which include mean radiant temperature, relative humidity, and air temperature and velocity, and human perception and preference towards the thermal conditions experienced (3). Human perception of thermal environments relies on



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multiple variables; including age, gender, clothing levels, metabolic rate, and activity (e.g. sedentary in office environments). Analyzing data for both aspects (physical and human), helps determine thermal comfort of occupants.

Indoor air quality (IAQ) is a significant factor that affects occupants' health and wellbeing hence influences productivity in office spaces. IAQ encompasses ventilation rate, air constituents and pollutants in a space. Research has confirmed that productivity in the workplace is affected by poor IAQ and confirms the significance of occupants' perception of air quality and how it affects their health and productivity (3). Concerning the impact of office layout on occupants' productivity depending on how it facilitates organizational work flow; mixed mode office layouts comprised of cellular and open plan office spaces have been suggested as the optimum solution to facilitate privacy, comfort and flexibility (2). However, with the open plan office layout comes the problem of noise which may have negative impacts on occupants' productivity. Occupants' overall perceived comfort has a positive correlation with perceived change in productivity. Workers may also tend to tolerate certain indoor environmental conditions if they have positive workplace experience and expectations (4). Hence, analysing indoor environments of existing workplaces will help identify interventions for improving building performance and occupants' comfort.

Buildings consume around 40 percent of all energy resources, whereby around half is used for heating and cooling of buildings. Solar design can provide the building envelope with a new function where the shading elements becomes an active component of the building. Solar shading systems have the potential to influence cooling energy loads – particularly in fully glazed office buildings. Uncontrolled solar radiation in workspaces affects workers' thermal and visual comfort and reduces productivity due to potential overheating. In order to combat this issue external solar shading systems can be implemented or integrated on to the façade of fully glazed office buildings. However, solar shading design is challenging as it needs to be designed with multiple variables in mind; building location, orientation, solar azimuth and altitude, fenestration / glazing types, sizes and location. Smart solar shading systems should ideally allow the low winter solar altitudes and block the high summer solar altitudes (5).

Overhangs are a common strategy of solar control where one of the main advantages is that they have minor or no obstruction of views outside. However, they may have limited effect particularly if they are fitted on the top floor of a multistory building. Louver systems can also be implemented horizontally or vertically depending on the façade orientation. Louver systems can either be fixed, moveable or automated and may be operated by the building management system (BMS) which monitors and responds to the whole building performance.

It has been asserted that simple and inexpensive fixtures of window glazing and shading devices significantly contribute to improved daylight quality and controlled solar radiation for optimised visual and thermal comfort (6,7). These simple techniques such as solar screens, roller blinds and venetian blinds may be used in office buildings for its simplicity and affordability. The mechanism of these shading devices is to control the solar radiation and the natural light intensity and distribution in the building interior spaces. Light guiding systems LGS are devices that have been designed to perform in a responsive way to climatic conditions compared to the conventional shading systems. They are efficient in the reduction of the excessive solar gain without the prevention of diffused skylight transmittance. LGS categories include light shelves, fixed louvres, light directing louvres or glass and light guiding shade that can be mounted at the upper part of a typical window to enable full solar shading control. Other advanced types of LGS are curved slat profiles, variable angle configured slats, compound parabolic concentrating (CPC) reflective window blind system, highly reflective lamellas with retro reflection, anidolic solar blinds, and semi-transparent acrylic profiles (7). Systems of LGS are designed to track the sunlight at different angles, such as, blinds with different slat angles, reflective, mirrored or translucent louvres, reflective window sills, combined prismatic louvre and reflective blind system, holographic films on movable louvres, movable louvre variable-area light-reflection assembly (VALRA) system, transparent shading device, and sun-tracking prismatic system (7).

Louvers or blinds are one of the most widely used LGS category. Research indicates that facades with dynamic solar shading would perform better than fixed shading devices concerning total energy demand and occupants' comfort. However, dynamic active systems of louvers and blinds are not being widely used partially, due to the significant cost of installation and maintenance. Exterior slats are usually composed of stainless steel, anodized aluminium or Polyvinyl chloride (PVC) (8). The slats can be modelled to have a cross section of a rectangle or curved segment according to design specifications. The slat size and distance between slats and the type of fixation differ according to the location of the shading required and the associated solar altitude. Louvers and blinds may help in improving the distribution and control of daylight and sunlight throughout a space but potential glare should also be considered within the design. Glare is one of the issues that may be experienced in workspaces with excessive amount of glazed facades. Glare normally occurs when uncontrolled direct and reflected solar radiation accesses the building transparent envelope causing direct and indirect glare to occupants (9). The glare and daylight control may be achieved by controlling the variables of the cut-off-angle of direct radiation, the geometry of the shading device and the reflectance and transmittance of its material (6).

The purpose of this paper is to investigate the efficiency of an office building to fulfil its purpose as a comfortable and productive working environment. This will be tested by adopting a quantitative research methodology involving a questionnaire of the building users, and modelling and simulation of the case study in order to test the influence of the existing shading design of the building and explore potential interventions that could help improve occupants' comfort.

2. Research methodology

The aim of this study is to determine optimal strategies for improving the comfort of an office building, in order to make it more energy efficient and enhance the wellbeing, health and productivity of the occupants. The study will achieve this through a quantitative research methodology with concurrent data collection techniques applied to the case study building. This research project is undertaken in two phases: the first phase sets out to assess the overheating risks and issues with indoor thermal comfort. The questionnaire survey was carried out to assess occupants' experience and satisfaction in their working environment. This detailed information is then correlated to the dynamic simulation modelling using Integrated Environmental Solutions (IES) software suite to provide an in-depth understanding of the impact of material properties used in energy efficient building systems on building energy performance.

2.1. Case Study: Newham Dockside

Originally designed as the Royals Business Park project in 2002 by Aukett Swanke Architects before then becoming the Newham Dockside which houses several of Newham Council departments. It is a large office building in East London of a total area of 28,6660 m², comprised of 4 floors and a ground floor. The ground floor has a Café and a restaurant besides other amenities such as a print and post room, and flexible open spaces. A large atrium splits the building into two wings; East and West which mainly comprise of open plan office spaces, enclosed meeting rooms and associated services. Due to the location of the building overlooking the Docks from the south façade and opposite London City Airport (LCA), it is not affected by any shadows from any nearby buildings. The design of the structure does not include any openable windows hence the use of extensive mechanical heating and cooling energy. Heating is provided by Heatrae Sadia megaflo with insulated pipes with Lochinvar of 379 litres capacity. There is a mechanical air-conditioning system with chillers, and supply and extractor fans. Lighting systems are compact and passive infrared (PIR) sensor. Manual internal blinds over the glazed façade is the only form of shading device used to control excessive direct and indirect solar radiation. The dockside receives high amounts of indirect solar radiation during the summer by reflecting off the water surface into the internal spaces. The building primary structural system is steel frames with a concrete precast panel system to form the building plinth. The façades are mainly

double-glazed acoustic performance aluminium frame and glass curtain wall with anodised aluminium brise-soleil louvres and brackets fixed back to the curtain wall.

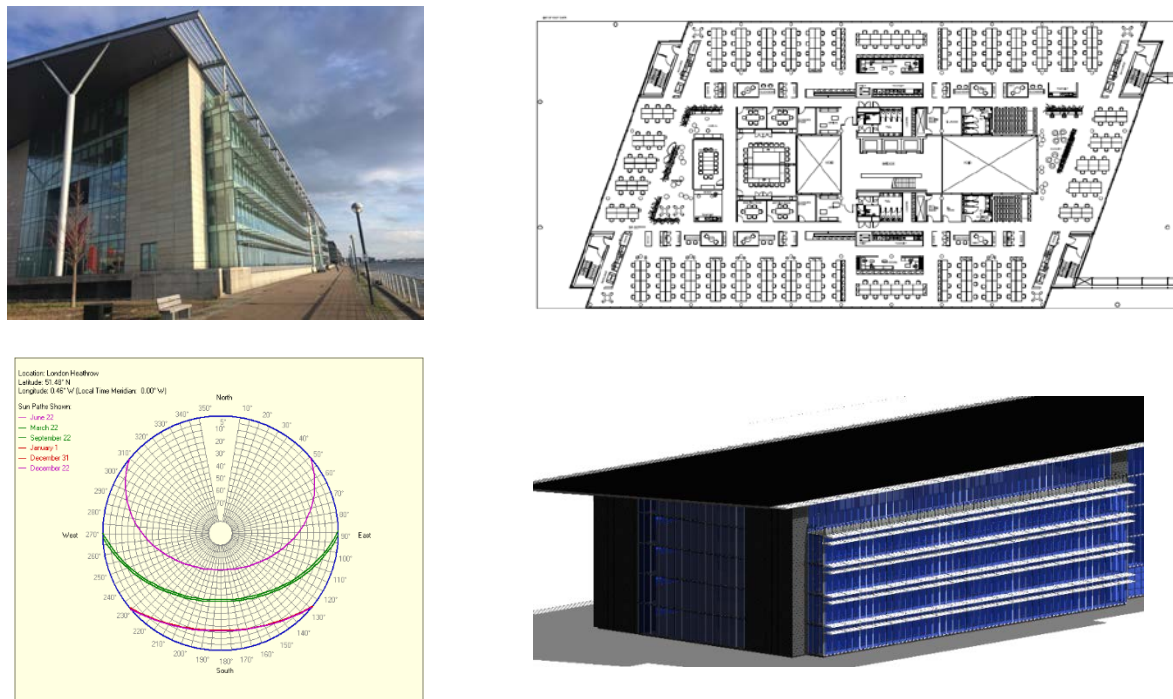


Figure 1. Image of the south and west facades illustrating the overhang and louvers (Authors) (a), Third floor (west wing) floor plan (Newham Council) (b), Sun path orthographic diagram for London (IES, 2020) (c), and case study Revit model (Authors) (d)

2.2. Questionnaire survey

The first research method used in this study is an occupant survey. Occupants were requested to fill in a digital questionnaire including questions on their usage patterns and behaviour, perceived comfort, perceived indoor air quality, and any other issues experienced in the building. This is mainly quantitative with closed-ended questions and only a couple of qualitative open-ended questions. Occupants were also asked how they adjusted their environment to make it more comfortable, e.g. occupants were asked when they opened windows and if they had any additional heating or cooling appliances in their offices such as fans or electric heaters. Occupants were also asked open ended questions such as; ‘How do you think the thermal comfort of your office could be improved?’. The questionnaire was distributed to the building users over a period of 4 weeks in May 2017. A total of 66 responses were received due to many users being on annual leave. The survey results showed that many occupants suffered various issues of discomfort in their office spaces.

2.3. Modelling and simulation

Dynamic thermal modelling using Integrated Environmental Solution Virtual Environment (IES-VE) was employed for in-depth investigation of the building thermal performance and to facilitate data triangulation with the survey analysis and indoor monitored data. The building performance evaluation software package; using Apache-Sim in IES software suite for dynamic thermal simulation (DTS) was performed. The building was firstly modelled on Autodesk Revit 2020 where input parameters required for modelling included the building geometry and properties of the construction materials, specifications of the building components, occupancy patterns, internal heat gain sources, and the outdoor air temperature. The building geometry was created using detailed construction drawings provided by the building facilities manager where each floor is modelled to include its specific thermal

zones. The outcome is twofold; first, a validation of the initial simulations of the base case against the occupants' indoor experience; and second, an investigation of appropriate solar control interventions aiming to improve occupants' thermal comfort, reduce overheating risks and cooling energy loads.

3. Results and discussion

3.1. Questionnaire survey results

The questionnaire-based survey was conducted with occupants of the case study building during May 2017. Overall, 66 responses were collected comprising of almost 50% females and likewise males. Thirty percent of respondents' age is between 35-44, 26.7% between 55 and 64, whereas 18.3% are between 25 and 34 and likewise between 45 and 64 years of age. Concerning respondents' office location; 38% are based in the East Wing, 30% are based in the West Wing, whereas 15% are based in the West Wing opposite the DLR, and 13% are located in the West Wing opposite LCA. The results show that 44% of respondents usually felt hot, warm, or slightly warm during the working hours in the summer in their office spaces. Fifty one percent would prefer to feel cooler, or much cooler than they currently feel in the summer. Forty-eight per cent of respondents reported they use portable fans as secondary cooling systems in their office spaces, while almost 38% of respondents always and frequently draw the internal blinds during the day; 51.4% of which are in the West zones of the building.

Open ended question results on how respondents thought the indoor environment could be improved:

The temperature control of the building is generally poor. On the South side it normally gets too hot but the north side can be too cold (at the same time of day). Glare is also a significant problem on the south side of the building with both direct sunlight and significant levels of reflection of the water. The air conditioning also seems to have a problem as I constantly seem to be suffering from colds (stuffy congestion and sneezing).

Less glass. The building acts as a greenhouse so is baking hot in the summer and cold in the winter. The air conditioning cannot cope with the variations.

There are solar gains in the buildings which can be improved by installing shading devices on the glassed walls.

As we are near the water, it is quite windy. Fresh air is not utilised enough in the building design. Air-con. works but doesn't take away the stuffy feeling of being in an office.

Opening windows would be great if possible.

The above comments by respondents indicate there are different problems with indoor comfort in different parts of the building. A study which simulated occurrences of overheating indicated that large window surfaces represent major sources of discomfort unless proper shading devices are installed (10). Natural ventilation (indicated as fresh air by respondents) and the ability to control window opening is also regarded as a significant variable in determining occupants' comfort and satisfaction with their indoor environment.

3.2. Building simulation results

Integrated Environmental Solutions Virtual Environment (IES) software suite was employed in the study due to its recognized reliability as a research-informed tool with minimal error margins that includes Model-IT, Sun-Cast, Apache-Sim, and Vista-Pro (9). The applications used are Apache-Sim in IES software suite for energy simulations, Sun-Cast to simulate solar heat gain on the building envelope, and the Vista-Pro/Comfort settings for assessing the adaptive comfort according to CIBSE Technical Memorandum 52 (CIBSE™ 52) guidelines. London Kew - ASHRAE Climate Zone weather file was used in the model as the case study location is east London.

The Sun-Cast solar exposure analysis (Fig. 2) demonstrates that the annual maximum solar exposure is on the roof surface (approximately 953 kWh/m²) followed by the south façade of the building (between 656 – 775 kWh/m²). The solar radiation on the west façade From the survey results it has been confirmed that the most susceptible areas to overheating are the south facing zones, followed by the west and east wings of the building. The Apache-Sim calculations, demonstrated in Fig. 3, indicate that the operative temperature (T_o) on all floors fluctuates between 24 – 34°C on all 4 floors, while T_o reaches 38 - 40°C on weekends when the air conditioning is turned off during the month of August. This indicates very high overheating risks in the building, which confirms employees' survey responses. However, the results are recorded for floor plans as open office space occupied on weekdays between 9am – 5pm with mechanical ventilation and internal heat gains from occupants, electric appliances, computers, and lighting.

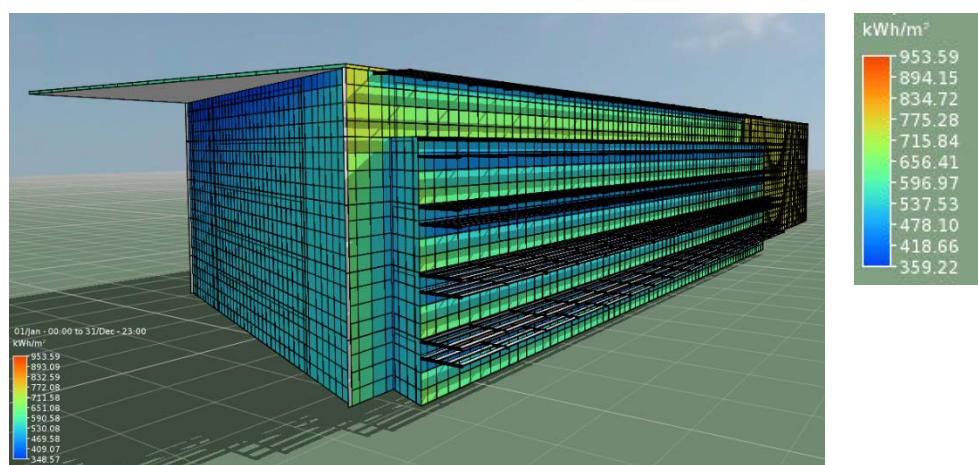


Figure 2. Sun-Cast simulation demonstrating the annual exposure to solar radiation on the south and west facades kWh/m² (IES, 2020)

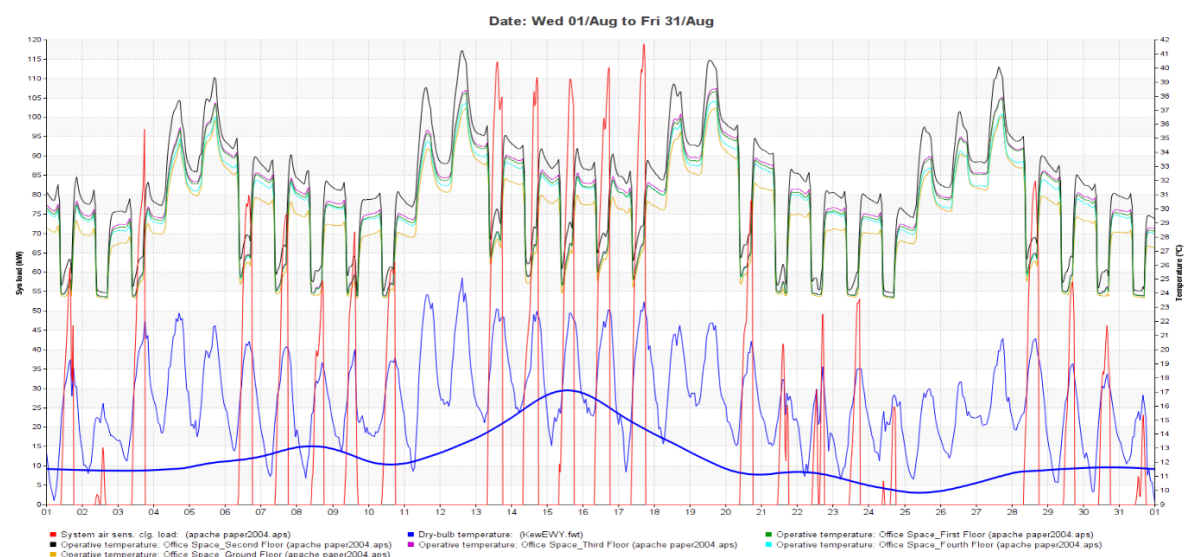


Figure 3. Apache-Sim calculations of the indoor operative temperature, and system load, besides the external dry bulb temperature during the month of August (IES, 2020)

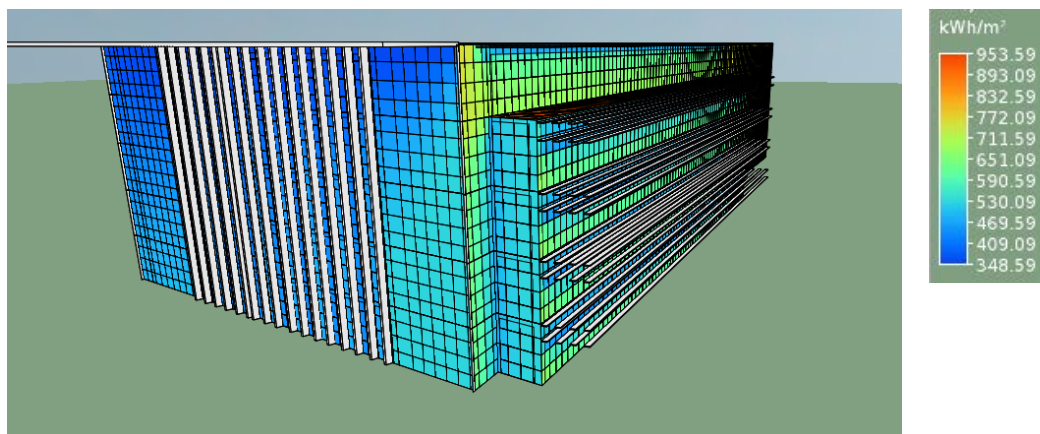


Figure 4. Sun-Cast simulation demonstrating the annual exposure to solar radiation on the west façade with added vertical fins kWh/m² (IES, 2020)

As demonstrated in figure 4, by applying vertical fins besides extending horizontal louvers on the south facade, the T_o reduces across the open floor office plans by an average of 2.4°C. The Building Regulations require that “reasonable provision shall be made for the conservation of fuel and power in buildings”. Within this is included a requirement to limit exposure to solar overheating or excessive solar gains [13]. Hence, further investigations will be undertaken in the case study to find more comprehensive solutions for improved indoor comfort.

4. Conclusion

The study sought to undertake an in-depth investigation into the building solar shading design and performance and the influence on occupants’ comfort of the case study building located in east London. The research attempts to contribute to the Sustainable Development Goals (SDG): SDG 3: Good health and well-being for people; via improving the quality of the built environment using sustainable design as a vehicle, and SDG 11: Sustainable cities and communities; by addressing the importance and relevance of benefits of solar responsive design across the wider community. A quantitative research has been designed based on data collected from a questionnaire survey, and modelling and simulation undertaken by Integrated Environmental Solutions (IES) software suite. The field study results indicate that the thermal comfort of the occupants of the case study building needs to be improved in summer months in order to fulfil its main purpose as a being a productive and healthy working environment for staff. The survey results show that the respondents are not thermally comfortable in their office spaces where it was mostly too hot for them in the summer months and for some too cold in the winter period. The results also demonstrated that the south, east and west facing offices have the most problems regarding the overheating risk in summer months. The results demonstrated that several zones of the building have been deemed uncomfortably warm with a lack of air movement in the summer months whilst other zones were found to be unacceptably cold and draughty in the winter months. This has been found to be due to the lack of adequate air flow coupled with lack of solar shading in some areas, and excessive draughts in other areas.

To reduce the overheating risk, it is vital to use the design strategies appropriate to particular climatic regions. It is also important to consider the local microclimate and the local architecture in building design when considering overheating risk in buildings (11) (12). These design strategies include appropriate shading devices, building orientation, thermal insulation, and thermal mass as well as appropriate glazing type and allowing for natural ventilation. In addition, reducing the overall heat gain from the occupants, electronic appliances and solar radiation in indoor environment may also significantly reduce overheating problems. Optimising natural ventilation and allowing user control is an effective way to improve the indoor thermal satisfaction. The effectiveness of natural ventilation on thermal comfort can increase when optimising the window characteristics including the size, position, transmission value, U-value and the type and location of shading devices. The performance of the

building material with regards to the heat capacity can be improved using night-time ventilation during the warm seasons to flush the heat transferred and retained within the building fabric during the daytime.

An unintended outcome of buildings which do not provide indoor comfortable, is that occupants may take measures such as using heating and cooling excessively in order to gain a satisfactory level of comfort. This will clearly undermine the energy efficiency of the building's design and performance. However, allowing occupants some control over their environment can improve the energy efficiency of office buildings. Hence, optimising the indoor environment in both existing and new buildings will enhance workplace performance and productivity.

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